Alcantara Study Enhanced Tectonic Characterization for Indonesia

Integrating SAR interferometry and GNSS for studying tectonic processes in Indonesia

Executive Summary

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ESA study manager: Philippe Bally

Alcantara Study Reference No.: 14-P16
Study Type: Pilot
Invitation to Tender: AO/1-8176/14/F/MOS
Contract Number. 4000114611/15/F/MOS

InSAR4Indo

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Contract No. 4000114611/15/F/MOS

ESA ITT AO/1-7864/14/F/MOS, Alcantara Study reference 14-P16 "Alcantara Study Enhanced Tectonic Characterization for Indonesia"

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December 2017

Document History		
Doc name: ExecutiveSummary-InSAR4Indo-ISSIA_Alcantara-14-P16.pdf	**Version:** Final release	**Date:** 12.12.2017

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1. Project overview

Indonesia is periodically affected by severe volcano eruptions and earthquakes, which are geologically coupled to the convergence of the Australian tectonic plate beneath the Sunda Plate.

SAR interferometry (InSAR) is a satellite technology based on RADAR sensors that can be used to support studying and modeling of terrain movements such as tectonic motions associated with faults, and volcanic processes related to magma movement. The main advantages of InSAR techniques are the synoptic view of wide areas, and the periodic surveying that guarantees long-term monitoring and time series analysis.

Multi-temporal InSAR (MTI) techniques provide both mean displacement maps and displacement time series over selected, stable objects on the Earth surface. Nowadays, historical SAR data acquired in different bands and from several satellite missions are available, and the launch of Sentinel-1A /B guarantees data for the next future.

The study of tectonic phenomena requires large-scale spatial analysis that poses challenges in MTI processing. A reliable modeling needs additional information coming e.g. from geodetic data, such as those provided by GNSS networks.

This project is aimed at performing an analysis of tectonic-induced surface displacements through InSAR MTI techniques over Indonesian test areas, selected according to the availability of historical SAR data, GNSS networks, and geological data.

The work includes:

- processing of historical SAR datasets through ad hoc MTI algorithms, selected depending on both the spatial scale of the phenomena, and the characteristics of the datasets;
- integration of geological information, GNSS measurements and InSAR deformation records for modeling tectonic and/or volcanic processes.

The project team is composed by the ISSIA institute of the Italian National Research Council (CNR) (Project leader), aided by the Physics Department of the University of Bari, Italy, which has experience on InSAR MTI processing, the Greek Institute of Geodynamics of the National Observatory of Athens (NOA), which provides expertise on GNSS data processing and integration, and the Irish SME Collaborative Space ltd., which ensures dissemination of the project scientific results and manages contacts with the local Indonesian personnel. Dr. Mustafa Elizar, from the Department of Electrical Engineering, Faculty of Engineering, Syiah Kuala University, Banda Aceh, Indonesia, serves as visiting scientific personnel, bringing knowledge of in situ conditions for the Indonesia test sites, and receiving training in remotely sensed data processing and integration.

Project activities were designed in consultation with the industrial partner, Collaborative Space, so that the technical and scientific findings could be used as building blocks of a pre-operational monitoring service. The inclusion of final users is one of the key objectives of the project. Indonesian institutions involved in the project include the Natural Disaster Research Centre and Tsunami and the Disaster Mitigation Research Center, and the Aceh Development Planning Agency, which is responsible for planning/operation.

2. The context

Although this project has a focus on scientific achievements, the local Indonesian community has since the beginning requested that special attention should be paid to tangible exploitation of the results. Several considerations can be made, spanning tectonics with the associated impact on tsunamis and landslides, to volcanoes.

The dynamics of the Java trench have historically produced different phenomena on both Sumatra and Java, such as the tsunami earthquake in 1907, off the coast of Aceh, and the two tsunami earthquakes south of Java occurred during the last 20 years. During several recent consultations, the expectations and the requirements expressed by both the scientific and final user communities have provided a good rationale for the use of Earth Observation to produce a better spatial assessment of tectonics, which in turn should be integrated with the use of local velocities derived from GNSS networks, to better picture local phenomena.

The majority of the casualties due to landslides are still associated with triggering factors such as heavy rainfalls, nevertheless in Indonesia the landslides triggered by earthquakes are known to take their toll on population.

Volcanoes are of very much concern on Java and Sumatra, and therefore expectations with regards to a possible integrated monitoring approach are significant. The potential value of this approach could be tested in a very well-known area such as the Merapi. Mount Merapi is the most active volcano in Java and has persistent minor eruptions, but according to volcanologists Mount Merapi is heavily overdue for a large-scale eruption, which could potentially put over 1.1 million people at risk.

The validity of the scientific results is a precursor to the actual uptake of the findings to be exploited thanks to a free and open data policy (when applicable), and to the use of processing platforms such as the ESA Geohazards Thematic Exploitation Platform. Because user uptake and its creation of business opportunities remains one of final objectives, the stakeholder composition for this project is made up by two scientific institutions: Tsunami and Disaster Mitigation Research Center (TDMRC) and Natural Disaster Research Centre PSBA–UGM, meant to cooperate towards the scientific achievements, and by a potential final user, namely the Aceh Development Planning Agency (BAPPEDA).

3. Test sites

A preliminary literature survey of the results obtained by other research groups through SAR interferometry and GNSS was carried out.

GPS stations from the of Continuously Operating Reference Stations (CORS) Indonesia network are found to be located in the area of interest. Investigations were carried out in order to check the format and the quality of the GPS records available. The Indonesian partner from Syiah Kuala University in Banda Aceh, and the Geodynamic Information Cluster of the Indonesian Geospatial Information Agency were involved in the process.

Based on the existence of a) onshore active faults, b) active volcanoes, c) deformation from GPS data, d) foreseen good interferometric coherence, e) availability of SAR imagery, f) the interest from the Indonesian partners, the following areas have been selected for MTI analysis:

1. Banda Aceh (Sumatra), hereafter referred to as Banda Aceh test site
2. Yogyakarta (Java) and Merapi Volcano (Java), hereafter referred to as Java test site

Figures 1 and 2 show, respectively for the Banda Aceh and the Java test site, the location within, respectively, the Sumatra and Java islands, the SAR data ground coverage, and the GPS stations available.

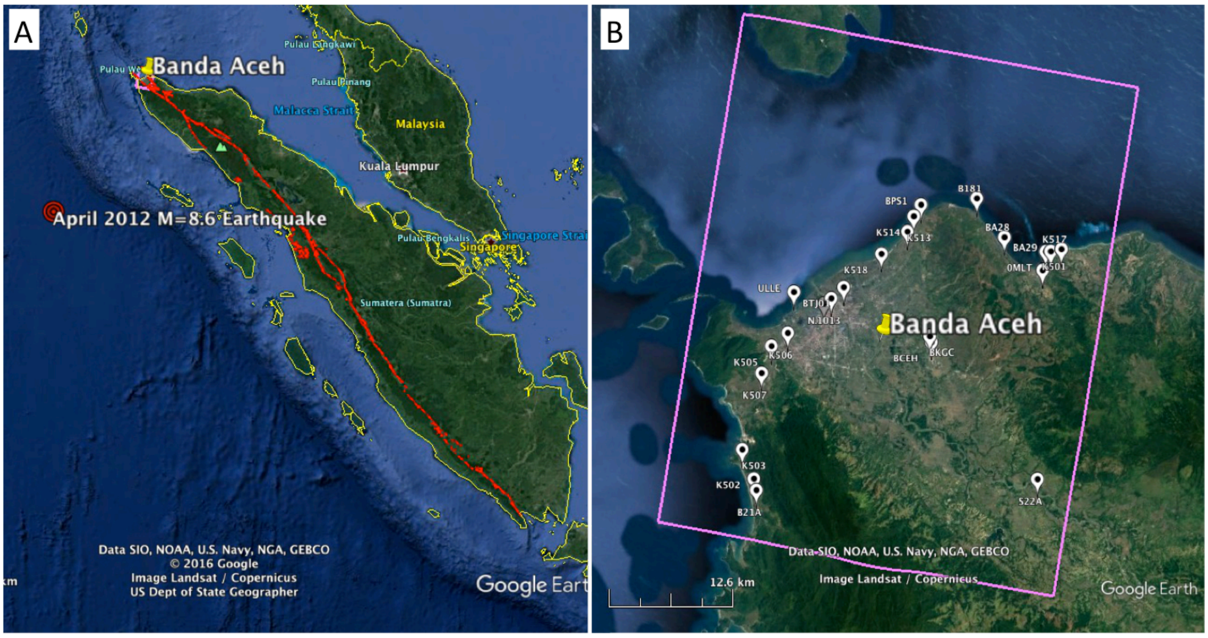

Figure 1. Location within the Sumatra island, SAR data ground coverage, and GPS stations for the Banda Aceh test site.

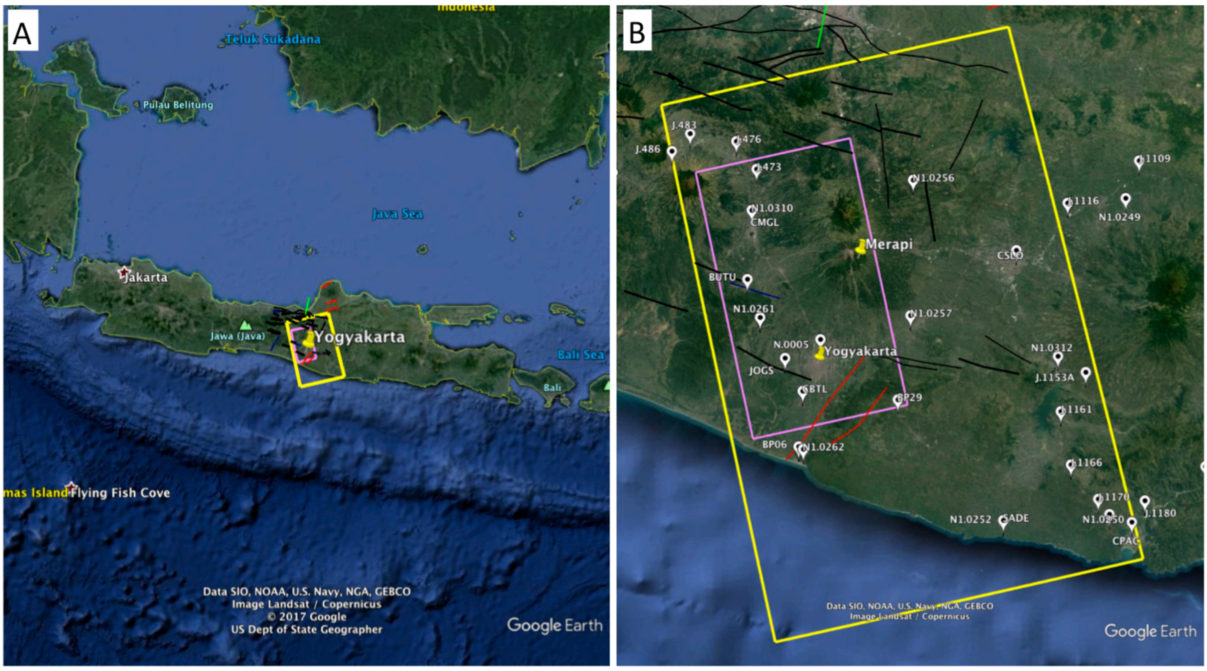

Figure 2. Location within the Java island, SAR data ground coverage, and GPS stations for the Java test site.

4. DInSAR processing and result analysis

Both the SPINUA (Bovenga et al, 2005) and the StaMPS (Hooper et al, 2004; Hooper et al, 2008) MTI algorithms have been used to process the data. The former is well suited for scarcely urbanized areas and high resolution local scale analysis, while the latter has been proven effective for studying both volcanic deformations and fault slip phenomena. This processing strategy allows to cross-validate MTI results, which is important in order to reduce artefacts due to either atmospheric signal or orbital errors. As already pointed out, these artefacts can affect MTI products obtained over wide areas, as often occurs when dealing with tectonic processes.

4.1. Banda Aceh test site

Due to the limited timespan of the project, MTI processing was performed by using archived SAR data. For the Banda Aceh test site For the Banda Aceh test site a stack of about 300 archived SAR data is available, acquired by CSK (CSK_H4-04_HH_RD_124) between May 2011 and October 2016 in Stripmap mode, along descending orbits and with a mean incident angle of 32.2°. 50 images were selected, covering the whole timespan with roughly regular sampling, except from 2 seismic events, which were covered each by a short-time SAR image pair. Concerning the Sentinel-1 images, at the time of selection very few acquisitions were available (6 ascending and 9 descending scenes).

The displacement maps derived by SPINUA and StaMPS are basically in agreement, showing a general stability of the area except for a few sites affected by local movements. Figure 3 shows the mean LOS velocity of the PS detected through the SPINUA algorithm and white circles surrounding the areas affected by local instabilities. High resolution data from CSK provide good density of measurable targets on the ground, thus improving the delineation of the spatial deformation pattern, and increasing the chances to capture signals related to local instabilities. Nevertheless, due to the presence of vegetation in the region, several areas are lacking PS.

The tectonic analysis in Banda Aceh is difficult because the vegetation cover in the area causes lack of PS along and across the faults. Moreover, the use of GPS data, which is important in such setting, was hindered since the records available are incomplete and unreliable due to limited observation time span. Nevertheless, the PSI results seem to confirm the inactivity of the Aceh fault segment, as foreseen by geodetic studies. On the contrary, the lack of PS along the Seulineum fault segment does not allow to measure the deformation occurring along this segment.

PS time series analysis was also performed to investigate the effects of the M=8.6 earthquake occurred offshore on April 2012 and modeled by using an Okada-type model. No motion was detected by looking at individual PS time series searching for co-seismic displacements across the date of the event. Excluding other causes, this result may support the idea that the Okada-type model over-predicts surface deformation and/or the Sunda and Indian plates are not fully coupled. Basides the use of interferometric results for assessing the tectonic activity, several ground displacements (mainly subsidences) have been identified in the Banda-Aceh region, which basically reflect local effects. By looking at the lithology of the area, it results that the PS location correlates with clastic sediments and pyroclastic rocks. The areas affected by ground instabilities in Figure 3 have been selected for an in-situ inspection. This activity was carried out by the Indonesian partner, and it is aimed at finding signs on the ground (e.g. cracks, fissures, tilting, maintenance works, etc.) potentially related to the instabilities.

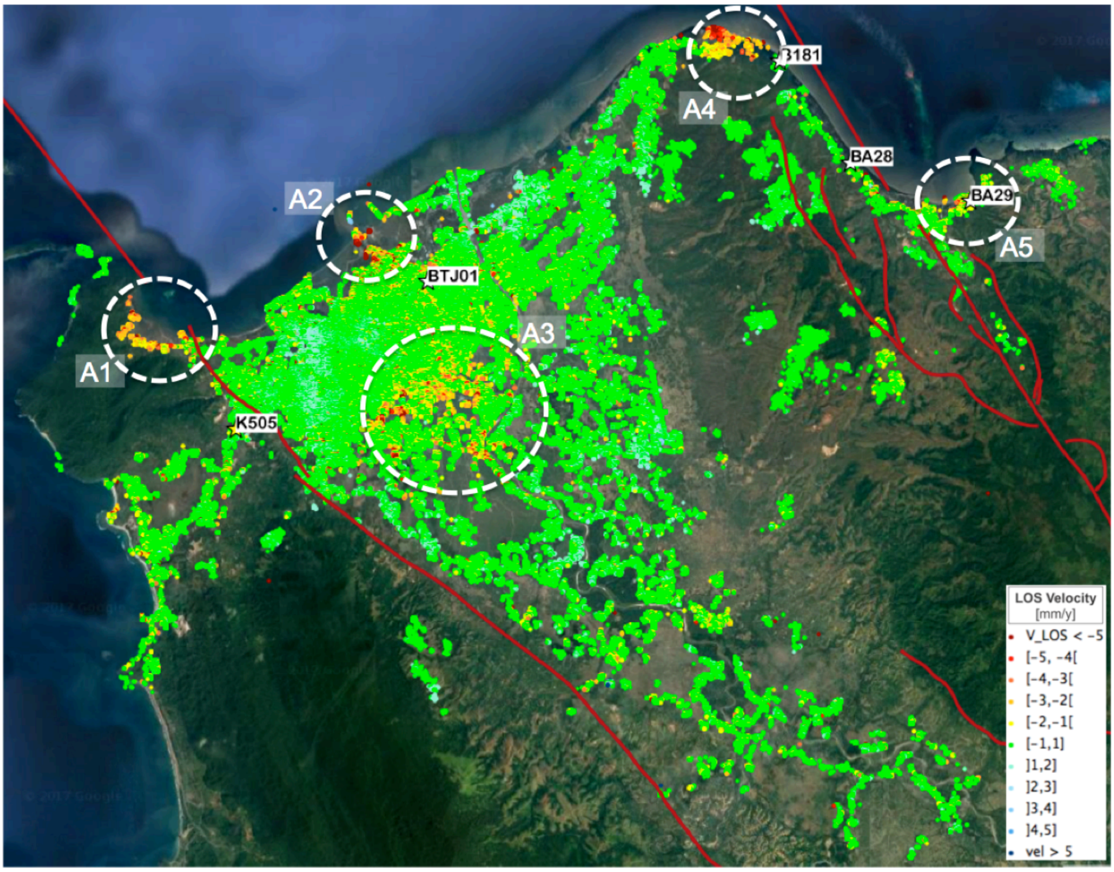

Figure 3. PS average LOS velocity maps over the Banda Aceh test site, obtained by processing COSMO-SkyMed data. Areas affected by local instabilities are indicated by white circles.

Sites A1, A4 and A5 (Figure 3) are coastal areas with loose unconsolidated sediments. Extensive presence of seasonally flooded crops (rice etc.) and salt production flats can be observed. Moreover, the possible presence of shallow groundwater pumping should be considered. According to this, the observed subsidence in these areas is probably related to the compaction of sediments. This is further confirmed by the fact that the deformation velocities derived by MTI are compatible with the rates of natural subsidence of unconsolidated sediments, which usually range roughly between 1 to 10 mm/yr. Moreover, the in-situ inspection assessed that PS targets showing high displacement rates correspond to buildings of recent construction.

A2 is a coastal strip with loose unconsolidated coastal sediments. Figure 4 shows PS average LOS velocity maps over this area. Inner panels show a PS displacement temporal trend. This part of Banda Aceh was overrun and completely destroyed by the 2004 tsunami. Most subsidence points are positioned on port facilities structures and embankments. Extensive rebuilding and new constructions in the area add weight to the unconsolidated sediments. There is also an extensive presence of seasonally flooded crops (rice etc.) and salt production flats. This suggests that the subsidence occurring in the area is probably related to compaction of sediments and/or recent artificial fill.

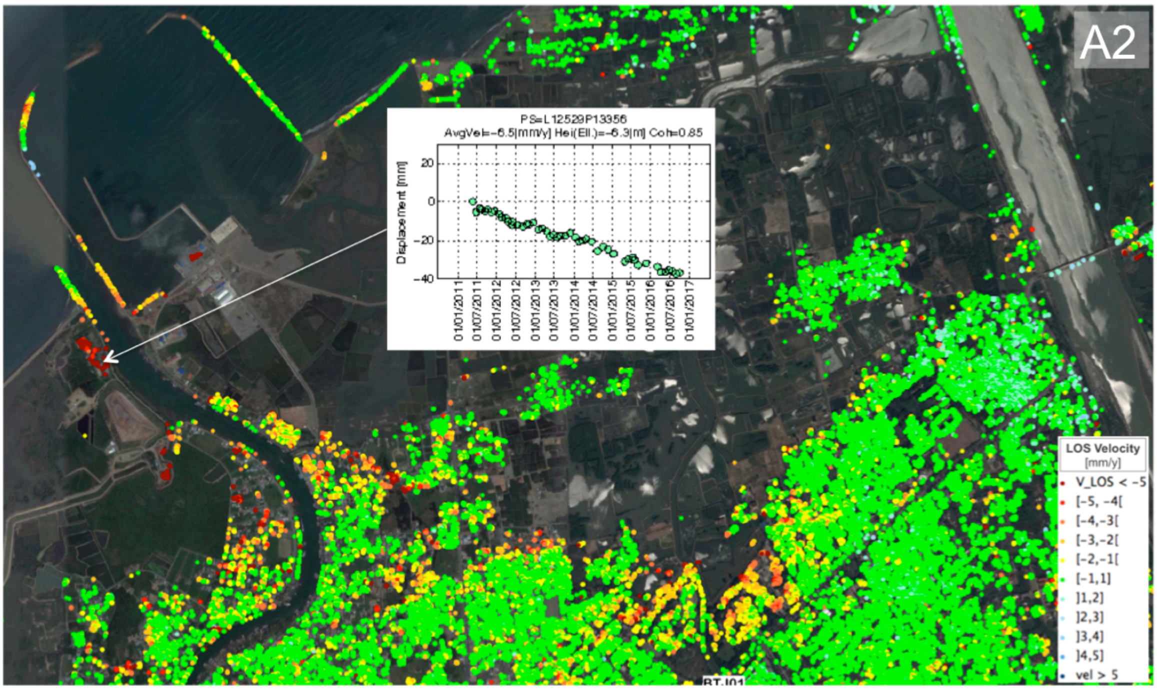

Figure 4. PS average LOS velocity maps within the area in the Banda Aceh test site labelled as A2 in Figure 3. The inner panel shows the displacement temporal trend of a coherent scatterers indicated by the white arrow.

4.2. Java test site

For the Java test site, reliable datasets are available from both COSMO-SkyMed and Sentinel-1 missions. Concerning the COSMO-SkyMed constellation, a stack of 97 archived SAR data is available (CSK_H4-03_HH_RA_175), acquired between December 2011 and November 2016 in Stripmap mode, along ascending orbits and with a mean incident angle of 29.3°. 50 images were selected from 02.05.2013 to 11.06.2016 (timespan of 37 months) covering the whole timespan with a roughly regular sampling and avoiding the large gap between 26.06.2012 and 02.05.2013. Concerning the Sentinel-1 constellation, a stack of 41 SAR data is available, acquired between 14.10.2014 and 31.05.2017 (timespan of 31 months) in Interferometric Wide Swath (IW) mode, along ascending orbits, and with a mean incident angle of about 33°. Thanks to the policy of Sentinle-1 ESA mission, no limitation exists on the number of images available for the processing. According to this, all the images have been used: the mean revisit time is 24 days in the whole time span, while just in the last period (three months) it reduces to 12 days.

Figure 5-A shows the mean LOS displacement velocity maps detected by processing COSMO-SkyMed data. The Persistent Scatterers (PS) targets are represented as dots superimposed on an optical image derived from Google Earth. The color depends on the mean LOS velocity according to the colorbar sketched in the same figure. Thanks to the high spatial resolution of COSMO-SkyMed the detected PS targets cover almost the whole region of interest. Few areas on the ground are lacking PS basically because of vegetation presence. Particularly affected by PS lack is the Merapi volcano due to the vegetation covering its flanks, as usually occur in volcanic areas. The displacement maps derived by SPINUA and StaMPS are basically in agreement showing a general stability of the area expect for few sites affected by local movements, as for instance the subsidence occurring in the Yogyakarta city (the area surrounded by white circle in Figure 5-A and labelled as A1).

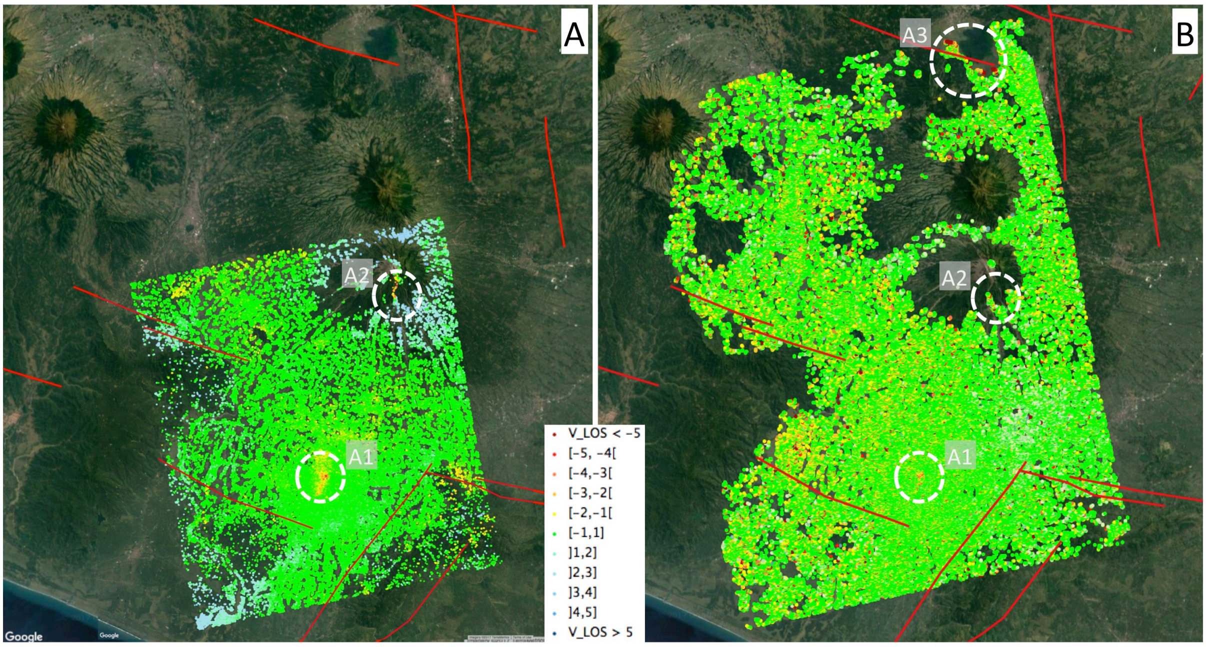

Figure 5. PS average LOS velocity maps over the Java test site, obtained by processing COSMO-SkyMed data (A) and Sentinel-1 data (B) through the advanced algorithm . Areas affected by local relevant instabilities are indicated by white circles.

The processing of Sentinel-1 data has been more complex with respect to that of COSMO-SkyMed data. By running standard MTI processing through both SPINUA and StaMPS the final displacement maps showed strong artefacts not related to reliable ground deformation pattern. In order to overcome this problem an alternative processing scheme has been experimented and integrate into SPINUA as detailed in the following section. In particular, a high pass spatial filter has been designed and implemented. It works on the complex interferograms, thus avoiding phase unwrapping, and possible related errors. The size of the spatial window can be set according to the residual signal to be filtered out, and to the expected ground deformation.

Figure 5-B shows the mean LOS displacement velocity maps derived by processing the Sentinel-1 dataset through the advanced procedure. The Persistent Scatterers (PS) targets are represented as dots superimposed on an optical image derived from Google Earth. The color depends on the mean LOS velocity according to the colorbar in the same figure. By comparing this product with the previous one in Figure 5.4, it is evident that no residual signals due to unfiltered atmosphere or orbital errors are now visible. Moreover, the displacement maps derived by processing COSMO-SkyMed data (Figure 5-A) and Sentinel-1 data through the advanced procedure (Figure 5-B) are basically in agreement, showing a general stability of the area except for few sites affected by local movements. This further confirms the effectiveness of the refined processing step integrated into the SPINUA chain.

PS point coverage is significant, due to the presence of urban and small settlements and agricultural activity in the area, resulting in the removal of most vegetation cover. Recent volcaniclastic deposits and areas scourged from recent eruptions around Mt Merapi volcano favour conditions for permanent scatterers.

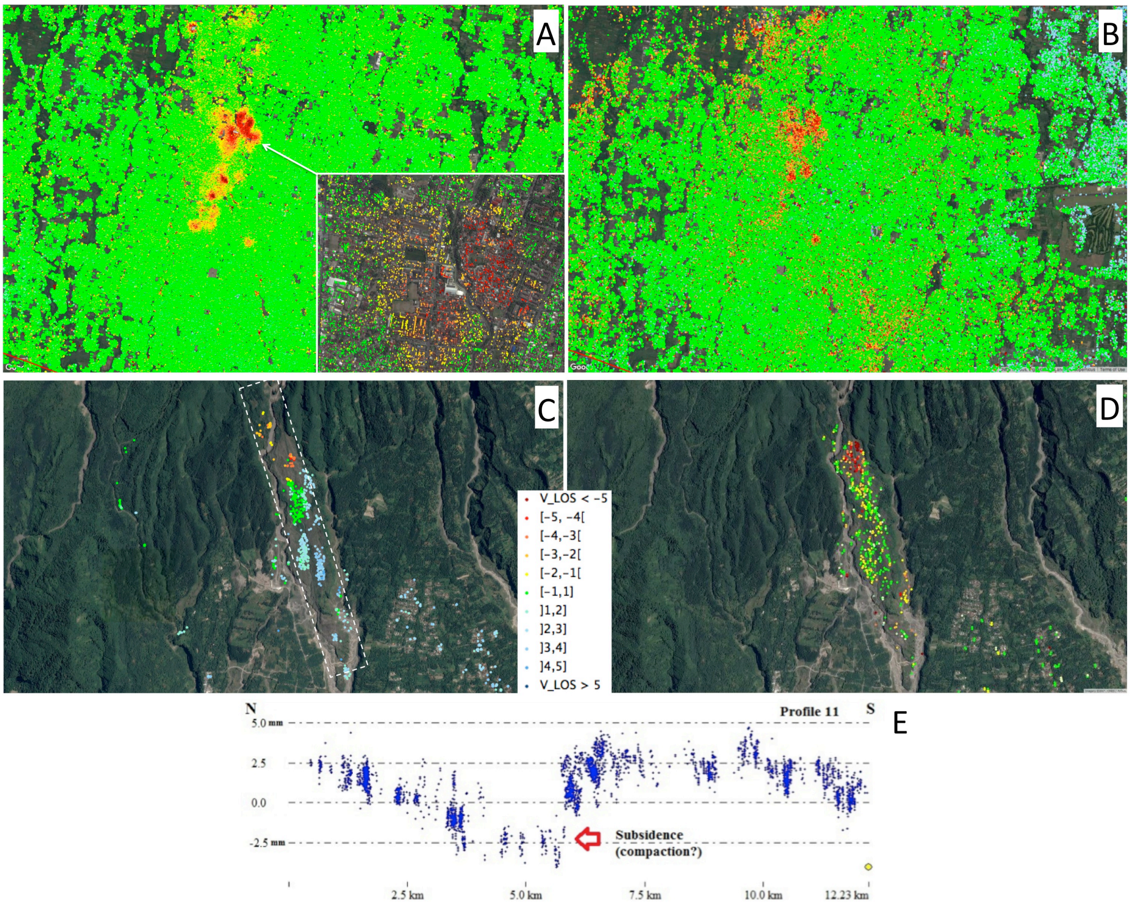

Figure 6. Top: PS average LOS velocity maps around the Yogyakarta city (area labelled as A1 in Figure 5) in the Java test site, obtained by processing COSMO-SkyMed data (A) and Sentinel-1 data (B) through the advanced algorithm. Bottom: PS average LOS velocity map on the flanks of the Merapi volcano (area labelled as A2 in Figure 5) in the Java test site, obtained by processing COSMO-SKyMed data (C) and Sentinel-1data (D) through the advanced algorithm. (E) Profile along the southern flank of Merapi volcano.

The displacements occurring in the area do not show any evidence of tectonic deformations around the faults sketched as red lines in the figures. Subsidence can be observed mainly in Yogyakarta urban area and occasionally, at alluvial plains around the area. Groundwater exploitation and soft sediment compaction are responsible for subsidence in these areas, a result of major urban expansion and human activity during the last years. Panels (A) and (B) in Figure 6 show the mean LOS displacement velocity maps around the Yogyakarta city (area A1 in Figure 5) derived by processing respectively COSMO-SkyMed and Sentinel-1 data. Both results reveal a subsidence affecting part of the urban area. The high resolution of COSMO-SkyMed data leads to high spatial density of the PS targets, and allows catching interesting details over urban structures as sketched in the panel in Figure 6-A.

Localised high subsidence rates are observed upon recent (2010) volcanic deposits at the flanks of Mt Merapi, a result of compaction of the soft explosive products (pyroclastic density currents and pumice). Panels (C) and (D) in Figure 6 show the mean LOS displacement velocity maps in the area labelled as A2 in Figure 5 and derived by processing respectively COSMO-SkyMed and Sentinel-1 data. Panel (E) shows the deformation profile along the southern flank of Merapi volcano obtained from the COSMO-SkyMed data.

5. Final remarks

The project test site selection has been carried out based on the existence of onshore active faults, active volcanoes, GPS data, foreseen good interferometric coherence, availability of SAR imagery, and the interest from the Indonesian partner. Two areas have been selected: an area around Banda Aceh in the Sumatra island, and an area including both the city of Yogyakarta and the Merapi volcano, in the Java island.

The collection of GNSS records took time, and was performed by involving the Indonesian partner from Syiah Kuala University in Banda Aceh, and the Geodynamic Information Cluster of the Indonesian Geospatial Information Agency.

The tectonic analysis in Indonesia is difficult because the vegetation cover in the area causes lack of PS along and across the faults. The use of GPS data, which is important in such settings, was here hindered since the records available are incomplete and unreliable due to limited observation time span.

The use of two MTI processing chains and of datasets coming from both COSMO-SkyMed and Sentinel-1 constellations, allow cross-validating final results. The processing of Sentinel-1 data has been more complex with respect to that of COSMO-SkyMed data, as standard MTI displacement maps showed strong artefacts, likely due to residual atmospheric contributions and orbital errors. This was imputed to the lower number of images and the shorter timespan covered by Sentinel-1 with respect to the CSK data. In order to overcome this problem, an alternative processing scheme has been experimented and integrated into SPINUA, adding a step that filters the differential phase fields composing the stack in order to preliminarily reduce atmospheric phase contributions. This approach, supported by successful results obtained on other test sites, allowed to obtain displacement maps from Sentinel-1 data consistent with those from COSMO-SkyMed data.

The MTI results provide useful information about the stability or instability within the selected test sites. In particular, concerning the tectonic activity in Sumatra, the PSI displacement analysis seems to confirm the inactivity of the Aceh fault segment, as foreseen by geodetic studies. Also, in the Java test site no displacement signal was detected related to possible activity of the faults present in the area.

In the Banda Aceh test site, PS time series analysis was also performed to investigate the effects of the M=8.6 earthquake occurred offshore on April 2012 and modeled by using an Okada-type model. No motion was detected by looking at individual PS time series searching for co-seismic displacements across the date of the event. This result implies that the Okada-type model over-predicts surface deformation and/or the Sunda and Indian plates are not fully coupled.

Besides the use of interferometric results for assessing the tectonic activity, ground displacements (mainly subsidences) have been identified both in Banda-Aceh region and in the Java test site, which basically reflect local effects. The causes of these displacements were investigated by using ancillary geological data, and, for the Banda Aceh test site, also by performing in situ inspections. The subsidence phenomena are likely mainly related to the presence of unconsolidated coastal/alluvial sediments and groundwater pumping.

For instance, by using both COSMO-SkyMed and Sentinel-1 data, subsidence can be observed in Yogyakarta urban induced by groundwater exploitation and soft sediment compaction, a result of major urban expansion and human activity during the last years.

Localised high subsidence rates are also observed upon recent volcanic deposits at the flanks of Mt Merapi, a result of compaction of the soft explosive products (pyroclastic density currents and pumice).

The strengths and weaknesses of the project have been analysed in the following.

- **Strengths**

  Multi Temporal Interferometry (MTI) techniques have been refined and used by processing both high resolution X-band SAR data (COSMO-SkyMed) and medium resolution C-band SAR data (Sentinel-1) for monitoring ground deformations. In particular Sentinel-1 data have been used to check the ground stability in Indonesian areas where both tectonic faults and volcanoes are present. Results have been validated by geological experts and in situ inspection performed by Indonesian researchers and potential users of satellite remote sensing data.

  The MTI processing chain has been updated in order to overcome problems deriving from the presence of strong atmospheric artefacts. The refined algorithm has been successfully tested by using Sentinel-1 data.

  The SPINUA MTI processing chain has been re-designed to be used by non-expert users on the ESA Geohazards Platform GEP. The porting of SPINUA algorithm has been successfully performed on the GEP virtual machine assigned to the project.

  The research activity was carried out with the successful support of Indonesian partners. The Indonesian team is composed by two research organizations (Natural Disaster Research Centre, Tsunami and Disaster Mitigation Research Center) and one responsible for planning/operation (Aceh Development Planning Agency). Dr. Elizar from Syiah Kuala University - Banda Aceh was actively involved in the project implementation, in particular for what concerns the integration of InSAR deformation maps with the deformation derived by GNSS, and the analysis of the final products. He was hosted in Bari for 2 months having a specific training on Interferometric SAR processing and its application to ground deformation monitoring, making available software tools and processing facilities. The collaboration with the Indonesian partner will continue after the project.

- **Weaknesses**

  The GPS records available in Banda Aceh and Java region are, at the moment, quite limited and incomplete, while an accurate knowledge of the ground stability is needed for monitoring the area. This is important in particular along the fault segments, in order to evaluate their capability of producing significant earthquakes.

  The possible use of satellite MTI in this context is twofold: it provides periodic ground displacement survey data where the land cover ensures coherent scattering conditions, and it can support the planning of optimal locations for new GPS stations.

Finally, in the following we summarize the outcomes of the project with respect to the specific objectives of the Alcantara study program.

- *Assess the level of maturity of the integrated approach based on SAR and GNSS: world-wide application that benefits from the satellite technologies.*

  The lack of reliable GNSS records makes difficult to experiment the integration of this in-situ measurement and the satellite SAR technology. Thanks to the periodic and global coverage of the satellite SAR mission, for some ground deformation phenomena (depending on the spatial and temporal scale), SAR interferometry can provide displacement indications where other in-situ measurement system are not available, and support to design GNSS network.

- *Assess the potential use of SAR satellite data and GNSS for studying tectonic processes: this is a target application for ESA Sentinel-1 mission.*

  Sentinel-1 data have been used to investigate the ground deformation in Indonesia where both tectonic processes and volcanoes are present. The lack of reliable GNSS records did not allow performing a fully integrated study. Nevertheless, the SAR data were used to assess the presence of ground displacements (not tectonic) over the areas of interest. The performance of SAR interferometry can be negatively affected by the presence of both vegetation and atmospheric artefacts, in particular when studying tectonic processes that require large-scale analysis. A properly designed GNSS network can provide valuable support to the InSAR processing in this contest.

- *Conduct tests beyond ESA member states thanks to research collaborations with Indonesia (a region strongly exposed to tectonic events).*

  The research activity was carried out in collaboration with Indonesian partners composed by two research organizations. They have supported the EU team in i) GPS data procurement; ii) in-situ inspection need to check the reliability of the InSAR-based deformation maps; iii) results interpretation. An Indonesian researcher had a specific training on interferometric SAR processing. The collaboration with the Indonesian partner is continuing with further training and publishing activities.